Method of processing seismic data acquired by means of
multicomponent sensors

GENERAL FIELD

5   The invention relates to techniques for processing
seismic data acquired by means of multicomponent
sensors.

This invention is in particular applicable to
10 acquisition by means of cables disposed on the bottom
of the sea (so-called "OBC" or "Ocean Bottom Cable"
techniques).

Multicomponent geophones capable of working in any
15 position whatsoever, in particular at the bottom of the
sea, have recently been proposed. This "omnitilt" probe
technology has allowed new simplified cables
(mechanical joints are no longer necessary) and allows
acquisitions with a better seismic bandwidth.

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However, the acquisition step does not make it possible
to provide the true orientation of the geophones of the
cable, although this information is indispensable for
making it possible to process the data.

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The invention proposes a processing which is intended
to be implemented on raw data and which allows
reorientation and calibration (intended to convert the
measurements of various geophones into a common phase
30 and amplitude response).

STATE OF THE ART

Techniques consisting in isolating from the signal the
35 data which correspond to the first arrival at the
sensor and in determining on the basis of these data a
filter intended to be applied to the raw data so as to
correct them and to thus obtain the components of the
signal on the expected axes have already been proposed.

A proposal to this effect has been described in the article:
"Horizontal vector infidelity correction by general linear transformation" - Joe Dellinger et al. - SEG - 9-14 September 2001.

However, this technique is not necessarily optimal since the coupling mechanism which intervenes at the geophone level is not the same for the waves which correspond to a first arrival at the sensor and for the waves reflected or converted by the seismic horizons.

PRESENTATION OF THE INVENTION

The invention proposes another approach which employs the true data window for numerically reconstructing geophones oriented along the desired axes.

Implicitly, this approach compensates for the errors which are not related to the geophones themselves, but which are due to the fact that the coupling between the geophone and the waves to be recorded is different depending on whether it is necessary to make a vertical vibration movement rather than a horizontal movement (on account of gravity).

In the case of a cable, the coupling is furthermore different depending on whether the vibration movement is in the direction of the cable or transverse.

Moreover, since deeper windows are subject to a lower S/N (signal-to-noise) ratio, processing which implements trace stacks is moreover used.

The invention thus proposes, according to a first aspect, a method of processing seismic data acquired by means of a sensor having at least three geophone components, characterized in that estimators are

determined which are combinations of these components
making it possible to isolate the various data
depending on whether they correspond to propagation
with reflection or with conversion and in that, to
5   determine a sensor reconstruction, the operators to be
applied to the various components of the sensor are
determined in such a way as to minimize the deviation
between reference data and data obtained by applying
the estimators to the sensor reconstruction, the
10 operators thus determined being applied to the data
acquired.

It is specified here that, in the remainder of the
present text, the term geophone is understood to mean
15 any velocity sensor and the term hydrophone any
pressure sensor.

Preferred, but non limiting aspects of the method
according to the first aspect of the invention are the
20 following:
-    the sensor furthermore including a hydrophone, the
reference data for reconstructing a vertical geophone
are derived from the data acquired by the hydrophone;
-    the reference data for reconstructing a vertical
25 geophone without hydrophone or for reconstructing
horizontal geophones are derived from the application
of the estimators to one of the geophones of the
sensor;
-    the orientation in the horizontal plane of a
30 geophone component is obtained by minimizing the
estimator of the transverse reflection;
-    the estimators are determined as a function of a
model of isotropic propagation or including the
azimuthal anisotropy.
35   - . ..

According to another more general aspect, the invention
proposes a method of processing seismic data acquired
by means of a sensor having at least three geophone
components, characterized in that estimators are

determined which are combinations of these components making it possible to isolate the various data depending on whether they correspond to propagation with reflection or with conversion. The estimators thus

5 determined may find applications other than that forming the subject of the method according to the first aspect of the invention.

DESCRIPTION OF THE FIGURES

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-    Figure 1 is a diagrammatic representation giving the angular conventions used;

-    Figures 2 and 3 are flow charts giving the various steps of the processing respectively in one and the

15 other of the two exemplary implementations described.

DESCRIPTION OF ONE OR MORE MODES OF IMPLEMENTATION OF THE INVENTION

20 **First exemplary implementation: case of an isotropic propagation model**

Under the assumption of a locally 1D (one dimensional) geology in proximity to the receivers, and assuming

25 isotropic propagation of the earth, a given geophone, with an orientation ϕ ψ, measures:

$$m_k = Rpp \cos(\psi)\delta pp_k + (Rps \cos(\theta_k - \phi) + Rtrsv \sin(\theta_k - \phi))\sin(\psi)\delta ps_k$$

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	With :	
k	:	index for the shotpoint (from 1 to N)
θ_k	:	azimuth of the shotpoint with respect to the abscissa axis
$-R_{pp}$	:	reflectivity PP
δ_{pp}	:	dynamic correction PP ("normal moveout" or NMO)
Rps	:	isotropic radial reflectivity PS

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Rtrsv   :   isotropic   transverse
reflectivity PS
δ_{PS} :   dynamic   correction   PS   ("normal
moveout" or NMO)

This model allows the evaluation of the reflectivity
parameters from the set of traces tr_k through simple
processing of least squares comparison (ignoring ψ to
begin with) in the Fourier domain, leading to the
following equations:

$$\begin{pmatrix} \dfrac{N}{wc(\varphi)} & wc(\varphi) & ws(\varphi) \\ \dfrac{}{ws(\varphi)} & Sc2(\varphi) & Scs(\varphi) \\ & Scs(\varphi) & Ss2(\varphi) \end{pmatrix} \cdot \begin{pmatrix} Rpp \\ Rps \\ Rtrsv \end{pmatrix} = \begin{pmatrix} Svx \\ Shcx(\varphi) \\ Shsx(\varphi) \end{pmatrix}$$

Scalar quantities:

$Sc(\phi) = \Sigma_k \cos(\theta_k-\phi)$ $Ss(\phi) = \Sigma_k \sin(\theta_k-\phi)$
$Sc2(\phi) = \Sigma_k \cos^2(\theta_k-\phi)$ $Ss2(\phi) = \Sigma_k \sin^2(\theta_k-\phi)$
$Scs(\phi) = \Sigma_k \cos(\theta_k-\phi) \sin(\theta_k-\phi)$
$N = Sc2 + Ss2$

Wavelet quantities:

$wc(\phi) = \Sigma_k \cos(\theta_k-\phi) \delta ps_k \, \delta pp_k^{-1}$

$ws(\phi) = \Sigma_k \sin(\theta_k-\phi) \delta ps_k \, \delta pp_k^{-1}$

Trace stack quantities for geophone x:

$Svx = \Sigma_k x_k \delta pp_k^{-1}$
$Shcx(\phi) = \Sigma_k \cos(\theta_k-\phi) \, x_k \delta ps_k^{-1}$
$Shsx(\phi) = \Sigma_k \sin(\theta_k-\phi) \, x_k \delta ps_k^{-1}$

The solution of this linear system gives:
$\Delta iso\ Rpp\ \cos(\psi) = W\ Svx + (Scs\ ws-Ss2\ wc)Shcx + (Scs\ wc-Sc2\ ws)Shsx$
$\Delta iso\ Rps\ \sin(\psi) = Kis\ \cos(\phi) - Kic\ \sin(\phi)$

$$\Delta iso\ Rtrsv\ \sin(\psi) = Kis\ \cos(\phi) - Kic\ \sin(\phi)$$

With:

$$W = Sc2\ Ss2 - Scs^2$$

$$\Delta iso = WN + wc(Scs\overline{ws} - Ss2\overline{wc}) + ws(Scs\overline{wc} - Sc2\overline{ws})$$

$$Kic = (Scs\overline{ws} - Ss2\overline{wc})Svx + (NSs2 - ws\overline{ws})Shcx + (-NScs + ws\overline{wc})Shsx$$

$$Kis = (Scs\overline{wc} - Sc2\overline{ws})Svx + (-NScs + wc\overline{ws})Shcx + (NSc2 - wc\overline{wc})Shsx$$

This modelling allows evaluations taking account of the following properties:

a.   Rpp does not depend on ϕ,

b. $|Rps|^2 + |Rtrsv|^2$ does not of course depend on ϕ either,

c. Δiso is in practice rapidly steady over time and can be ignored for the calibration/orientation procedure, since it is common to all the geophones of one and the same receiver.

Evaluations of dense shots

Most of the OBC acquisitions are gleaned using a dense and regular grid of sources, which allows considerable simplification:

Sc = Ss = 0, wc = ws=0 (symmetry of the sources with respect to the receivers)

Scs = 0 Sc2 = Ss2 = N/2 (isotropic source distribution)

Next, the exact solution can be obtained through the approximation:

N Rpp cos(ψ) = Svx

N Rps sin(ψ) = 2 Shcx(ϕ)

N Rtrsv sin(ψ) = 2 Shsx(ϕ)

This approximation leads to very simple calculations, not involving any wavelets, and can be applied immediately.

Orientation of the geophones

Since Rtrsv does not exist physically, the minimization
of the energy of Rtrsv leads to a trigonometric
equation which gives the true orientation $\phi_{geo}(+k\ \pi)$:

5   $\tan(2\ \phi_{geo}) = 2\ (\sum_i Kic_i\ Kis_i)/(\sum_i Kic_i^2 - \sum_i Kis_i^2)$

$((Emax-Emin)/(Emax+Emin))^{1/2}$ gives   a   check   on   the
quality of the reorientation.

10 Moreover, if one wishes to find the orientation
according to the first arrivals, it is possible to
correct the said first arrivals so as to set them to
one and the same arrival time, then to simplify kic and
kis by replacing the wavelets wc and ws by the scalars
15 sc and ss, by considering that the waves recorded
horizontally are in fact the projection of the radial
wave P, present on all the geophones since it is
oblique.

20 Geophone vertical composite calibration:

With the geophones g_1, g_2, g_3, we construct a vertical
composite geophone v, $v = op_1*g_1 + op_2*g_2 + op_3*g_3$ (or
comprising additional similar terms in the case where
25 extra geophones are present in the receiver) where op_1,
op_2, op_3 are the filters of finite length and op_u*g_u
represents the convolution of geophone g_u with filter
op_u.

30 such that:

$E1 = |XH - XV|^2 = |Kic(v)|^2 + |Kis(v)|^2$

The energy of the difference between XH (hydrophone
35 after application of the geophone phantom, or
cross-ghost hydrophone) and XV (the vertical composite
geophone after application of the hydrophone phantom or

cross-ghost geophone), (see for example in this regard the Applicant's Patent Application FR 2 743 896).

$$E2 = |Rps(v)|^2 + |Rtrsv(v)|^2$$

horizontal energy of the vertical composite,

$E = \lambda E1 + (1-\lambda)E2$ is a quadratic form in the coefficients of the filters and can be reduced to the minimum, thus giving a linear system to be solved. (λ is a matching parameter, $0 <= \lambda <= 1$, which favours either a greater adjustment to the reference hydrophone or a greater minimization of the shear energy).

In the case of terrestrial data, that is to say if there is no hydrophone available, it is possible to choose one of the geophones as reference and to replace the hydrophone by $Rpp(g_{ref})$.

Calibration in a horizontal arbitrary direction

With $g = op_1*g_1 + op_2*g_2 + op_3*g_3$ and φ_g an arbitrary direction,

We define:

$$E1 = |Rps(g, \varphi_g) - Rps(ref, \varphi_{ref})|^2,$$

as being the energy of the difference between the evaluation of Rps of the arbitrary composite geophone and the evaluation of Rps of a reference geophone (in general the geophone oriented in the direction of the cable).

$$E2 = |Rpp(g)|^2 + |Rtrsv(g, \varphi_g)|^2 \text{ (the nonradial energy)}$$

$E = \lambda E1 + (1 - \lambda)E2$ allows the derivation of a composite horizontal geophone in the desired direction, having the same frequency response as the reference geophone, and with a minimum PP contamination.

Considering the cases $\varphi_{ref} = 0$ and $\varphi_{ref} = \pi/2$, it is possible by simple trigonometric combination to generate the radial and transverse projections.

Second exemplary implementation: case of anisotropic azimuthal propagation modelling

Let α be the direction of the natural fast propagation axis. The modelling of the measurement of the geophone becomes (using one or other of Rps1 and Rps2 the two images along the natural directions, or Rps and δRps defined by Rps1 = Rps + δRps, Rps2 = Rps - δRps):

m_k = Rpp cos(ψ)δpp_k + (Rps1 cos($\varphi-\alpha$)cos($\theta_k-\alpha$) + Rps2 sin($\varphi-\alpha$)sin($\theta_k-\alpha$))sin(ψ)δps_k

m_k = Rpp cos(ψ)δpp_k + (Rps cos($\theta_k-\varphi$) + δRps cos($\theta_k+\varphi-2\alpha$))sin(ψ)δps^k

giving the normal equations

$$M = \begin{pmatrix} N & wc(\varphi) & wc(2\alpha-\varphi) \\ \overline{wc(\varphi)} & Sc2(\varphi) & Sc2(\alpha)-N\sin^2(\alpha-\varphi) \\ \overline{ws(2\alpha-\varphi)} & Sc2(\alpha)-N\sin^2(\alpha-\varphi) & Sc2(2\alpha-\varphi) \end{pmatrix}$$

$$M.\begin{pmatrix} Rpp \\ Rps \\ \delta Rps \end{pmatrix} = \begin{pmatrix} Svx \\ Shcx(\varphi) \\ Shcx(2\alpha-\varphi) \end{pmatrix}$$

The solution of this linear system gives:

Δiso Rpp cos(ψ) = unchanged
Δaniso Rps sin(ψ) = (Kac cos($2\alpha-\varphi$) + Kas sin($2\alpha-\varphi$))sin($2(\alpha-\varphi)$)
Δaniso Rtrsv sin(ψ) = (-Kac cos(φ)-Kas sin(φ))sin($2(\alpha-\varphi)$)

With:

Δaniso = sin^2(2($\alpha-\varphi$))Δiso

Kac = (Sc2$\overline{ws}$ -Scs$\overline{wc}$)Svx + (N Scs-wc$\overline{ws}$)Shcx - (N Sc2-wc$\overline{wc}$)Shsx

Kas = (-Ss2$\overline{wc}$ +Scs$\overline{ws}$)Svx + (N Ss2-ws$\overline{ws}$)Shcx - (N Scs-ws$\overline{wc}$)Shsx

Vertical calibration of composite geophone:

The isotropic process remains applicable with the change

$$E2 = |Kac(g)|^2 + |Kas(g)|^2$$

Horizontal arbitrary calibration or rows/columns of composite geophones

The observation of δRps over the data field makes it possible to diagnose the presence (or otherwise) of significant azimuthal anisotropy. (the quantity sin^2(2($\alpha-\varphi$))δRps does not require a knowledge of α for its calculation).

The isotropic process remains applicable with the changes

$$E2 = |\delta Rps(v)|^2 \text{ and } E = \lambda(E1+E2)+(1-\lambda)E3.$$

When α is not generally known, a scan over a range of $\pi/2$ is implemented, using the value of α which minimizes Emini/E0.